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Title: **Regional vastus medialis and lateralis activation in females with patellofemoral pain**

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ABSTRACT:

Introduction: To investigate whether regional activation patterns in the vasti muscles differ between females with and without patellofemoral pain (PFP), and whether muscle activation patterns correlate with knee extension strength.

Methods: Thirty-six females with PFP and 20 pain-free controls performed a standardized knee flexion-extension task. Activation of vastus medialis (VM) and lateralis (VL) was collected using high-density surface electromyography and analyzed using Principal component (PC) analysis. Spatial locations and temporal coefficients of the PCs, and percent variance they explain were compared between groups and between the concentric and eccentric phases of the movement. Correlations were assessed between PC features and knee extension strength.

Results: The spatial weights of PC1 (general vasti activation) and PC2 (reflecting vastus-specific activation) were similar between groups (R>0.95). Activation patterns in PFP were less complex than controls. Fewer PCs were necessary to reconstruct 90% of the signal for PFP participants in the concentric phase (p<0.05), and the difference in bias of activation to VM (concentric phase) or VL (eccentric phase) was less between phases for PFP participants (p<0.05). Smaller difference invastus-specific activation in concentric and eccentric phases (less task specificity of VM/VL coordination) was related to greater maximal knee extension strength (p<0.05, R<-0.43).

Conclusion: These data suggest PFP involves a simpler control strategy of VM and VL. The inverse association between task specificity and maximal knee extension strength suggests different presentations of PFP: lower knee extension strength but

VM/VL coordination task specificity comparable to controls, or knee extension strength comparable to controls but lower VM/VL coordination task specificity.

KEYWORDS: Patellofemoral pain; EMG; quadriceps; muscle strength; Principal Component Analysis.

INTRODUCTION:

Patellofemoral pain (PFP) is common in young individuals engaged in sports. It is a complex, multifactorial syndrome with a pathogenesis that has not been fully elucidated. Historically, poor patellar tracking due to unbalanced activation of the vastus medialis (VM) and lateralis (VL) muscles has been considered to contribute to PFP (1). Although some studies support this hypothesis (2–4), others have not identified differences in timing or amplitude of activation of vastii muscles between symptomatic individuals and painfree controls (5, 6). A systematic review of the literature highlighted 'substantial and unexplained heterogeneity' (7). This variability is likely to be explained by both physiological and methodological factors.

A possible contributor to this variability is the potential differences in muscle activation between clinical presentations. Common clinical findings of PFP include lower knee extension strength (8), lower hip muscle strength (9), and higher dynamic foot mobility (10). In addition, interventions focused on different sites such as knee muscle strengthening (11), hip muscle strengthening (12) and foot orthoses (13) have all been shown to improve PFP symptoms in the short term. One possibility is that altered quadriceps activation is more common in people with PFP who also have weak knee extensors. To our knowledge, no studies have tested whether altered quadriceps activation is associated with features of PFP clinical presentation.

Another factor that is likely to contribute to the unexplained variability of muscle activation in PFP relates to the methods used to quantify muscle activity. The technique most commonly used is surface electromyography (EMG), using one pair of electrodes placed on the belly of each vastus (2, 4, 5). This straightforward measure has a number

of limitations: for instance, due to variation in the location of the innervation zone relative to the electrodes, surface EMG amplitude differences up to 75% can be observed in the VM for electrodes positioned only 15 mm apart (14). Although this effect can be limited with normalization of EMG amplitude during isometric contractions (15), the VM innervation zone has been shown to shift under the electrodes as a function of knee angle (i.e. muscle length) (16), complicating the recording of representative surface EMG in dynamic contractions. In addition, as VM motoneurones innervate muscle fibres clustered within the muscle (17, 18), region-specific differences in VM activation can be observed both in reflex (19) and voluntary (16, 20) contractions; as regions within the vasti produce forces in different directions (21), differences in regional activation may result in different distribution of the forces applied to the patella.

Recent advances in EMG technology allow for the placement of up several tens of electrodes on single muscles (high-density EMG, HDsEMG). As signals are collected from different locations of the muscle, HDsEMG helps to overcome some limitations of conventional surface EMG. For instance, it is possible to take into account the effect of the location of the innervation zone and other anatomical factors on the estimation of neuromuscular activation (14), and to describe the activation of regions within a muscle (16). Specifically, regional muscle activation can be identified using factorization algorithms such as principal component analysis (22).

This exploratory study aimed to investigate whether VM and VL regional activation patterns, identified using high-density surface electromyography, differ between females with and without PFP. We hypothesized that, compared to painfree participants, those with PFP would demonstrate different coordination between VM and

VL as defined by spatial and temporal features of principal components extracted from VM and VL EMG activity during a standardized dynamic task. We also hypothesized that coordination between VM and VL would differ most in participants with lower knee extension strength. The research hypotheses were framed within contemporary theories on neuromuscular adaptations to pain, which predict that altered neuromuscular control is one factors that could sustain pain and function loss (23).

METHODS:

Participants:

Thirty-six females with symptomatic PFP and 20 healthy, sex-matched control participants were recruited from the local community and physiotherapy clinics. To be included in the PFP group, participants had to be: females, 19-35 years old, with retro- or peri-patellar knee pain of intensity equal or greater than 3/10 (on an 11-point numeric rating scale; 0 being ‘no pain’; 10 being ‘worst pain imaginable’) for at least 1 month aggravated by any of the following activities: sitting for long time periods, stairs, squatting, running, kneeling or jumping. They also needed to report pain or discomfort to at least one of the following tests: patellar palpation, patellar compression, resisted knee extension with knee close to full extension, isometric knee extension while applying pressure proximally to the patella. Control participants could not have had any knee pain in the last 12 months. For both groups, exclusion criteria were: previous lower-limb surgery, chronic neuromuscular disorders, or knee musculoskeletal disorders. All participants provided written informed consent before the start of the

experimental session. The study that was approved by the institution's Clinical Research Ethics Board.

Age, body mass, height, duration of pain (self-reported), average pain intensity in the previous week (11-point numerical rating scale; 0 = ‘no pain’; 10 = ‘worst pain imaginable’) were obtained for each participant. Physical activity (General Physical Activity Questionnaire, (24)) and functional limitation (Anterior Knee Pain score, (25)) were estimated using validated questionnaires. The test leg was the most painful knee (if both were painful) or a random leg for controls.

Clinical tests:

Dynamic foot mobility was assessed using the ‘foot mobility’ test. Following a validated and reliable procedure (26), foot arch height and midfoot width were measured using a caliper twice; while sitting and standing. The difference between measures taken in non-weightbearing and weightbearing positions was recorded and used to describe dynamic foot mobility.

Isometric knee extension strength was measured using a Biodex (System 4 Pro; Biodex Medical Systems, Shirley, NY). The hip and knee angles were standardized at 85° and 45° (0° being full extension), respectively, and the participants were secured firmly to the chair. The resistance was applied approximately 2 cm proximal to the medial malleolus. The participants were asked to contract maximally the quadriceps muscle of the leg tested, reaching a maximal contraction over 1-2 s to ensure a smooth contraction and to maintain it for at least 3 s. This procedure was repeated 3 times with at least 1 minute of rest in-between trials. Verbal encouragement was provided at each trial. The highest peak torque of the three trials was used as maximal knee extension

strength (KES); analyses were also run on the KES value normalized to body mass (nKES).

Protocol:

After a few repetitions to warm-up, participants performed 10 repetitive knee flexion-extension movements on the dynamometer from ~100 to 5° of knee flexion against a constant resistance set at 10% of their KES. A metronome standardized the pace at 3 s for each concentric knee extension, eccentric knee extension and rest.

Data collection:

Similar to a previous study (16), the HDsEMG grids were placed according to anatomical references (Fig.1). The medial and lateral edges of VM and VL were identified using ultrasound imaging (LogicScan 64 LT-1T; Telemed, Vilnius, Lithuania) and were marked on the skin. As thickness of the subcutaneous tissues between the electrodes and the muscle may influence EMG recordings, a single ultrasound image was also taken in the proximal and distal region of both muscles, approximately in correspondence of the proximal and distal third of the grid array. VM and VL innervation zones were located using a linear electrode array (16 silver bar electrodes, 10-mm interelectrode distance; OTBioelettronica, Torino, Italy) and marked on the skin. Two HDsEMG grids (semidisposable adhesive matrix; OTBioelettronica) were placed on the skin so that the innervation zone aligned between the second and third column, and all the electrodes were placed of the target muscle. Each grid comprised 64 electrodes arranged in 5 columns and 13 rows with a single electrode missing in one of the corners, 8 mm inter-electrode distance and was held in place using bi-adhesive foam. With this electrode position, activation of different muscle regions can be observed

along the columns of the electrode grid, with negligible influence of changes in VM muscle architecture associated with changes in knee angle joint (16). Reference electrodes (2x3.5 cm; conductive hydrogel; Kendall, Covidien, Mansfield, MA) were placed on the patella and on the medial and lateral epicondyles. HDsEMG signals were collected in monopolar modality using an EMG amplifier (128-channel EMG-USB; OTBioelettronica, Torino, Italy). Signals were amplified 500-1000 times, filtered (band-pass 10-750 Hz) and digitized at 2048 Hz using a 12-bit A/D converter. The knee position signal from the dynamometer was acquired simultaneously using the same amplifier.

Data analysis:

Ultrasound images were analysed using ImageJ (National Institutes of Health, Bethesda, Maryland, USA). The thickness of the subcutaneous tissues was measured as the distance between the skin and the most superficial edge of each muscle. All EMG analyses were run in Matlab 2016B (The MathWorks, Inc., Natick, MA, USA). A Butterworth filter (4^{th} order, 10-400 Hz) was applied to the EMG signals before processing. Envelopes were calculated for each channel of both HDsEMG grids by full-wave rectification and low-pass filtering at 8 Hz (Butterworth filter, 4^{th} order). For each participant, the EMG values corresponding to 10-90° of the knee flexion-extension repetitions were extracted, and envelopes were normalized to the maximal envelope value of all channels across VM and VL. EMG envelopes were concatenated in two matrices of 128 EMG channels by N samples (N = 20 or N = 36 participants, multiplied by time samples), one for the PFP group and one for the control group.

As the analysis aimed to identify regional activation within the vasti, Principal Component Analysis (PCA, (27)) was applied to the HDsEMG dataset. Removing the mean from the data before PCA did not change the results of the study, so the data are presented for non-centered data. In line with previous studies that used separate factorization analyses for different conditions or groups (28, 29), PCA was applied separately for PFP and controls. As opposed to running PCA pooling all participants together, this approach enables identification of between-group differences in spatial weights; but limits between-group comparison of temporal coefficients to PCs that have similar spatial weights (R>0.95 in this study). PCA identifies clusters of channels with large covariance in time, factorizing the signal in principal components (PC); PCs represent the general activation pattern (PC1) or the major ways in which this pattern could be modulated (PC2-4) at any instant in time. Based on a recent study (22), it is expected that PC1 will have only positive values and will describe a general VM/VL activation; instead PC2 and above will have both positive and negative values, and will describe how the activation of regions within VM and VL is modulated (i.e.: increases/decreases compared to PC1). Preliminary analyses showed that the first four components described patterns of activation of the four regions of interest in this study (proximal/distal VM; proximal/distal VL), hence four PCs were considered. Each PC can be described by three indices (Fig. 2; Fig. 3): 1) spatial weights: the location of the channels where the PC is most represented; 2) temporal coefficient: the time profile of the activation of the PC; 3) the variance explained: how much of the variance of the signal is accounted for by the PCA. Each EMG envelope matrix **M** was factorized into 128 PCs, each consisting of 128 weights and N coefficients. Spatial weights were

calculated as the eigenvectors $\boldsymbol{\zeta}$ of the covariance matrix of **M**. Temporal coefficients were calculated as $\boldsymbol{\zeta}^T * \mathbf{M}$, which is the matrix product between the transposed eigenvectors and the EMG envelope matrix. PCs were sorted according to their eigenvalues. Spatial weights, temporal coefficients and variance explained of the PCs extracted from the PFP and from the control participants were compared between groups. For each participant, the temporal coefficients of the first 4 PCs corresponding to the concentric and the eccentric phase of each repetition were identified and averaged across knee angles and repetitions. The coefficient of determination (CD=1-SSE/SST, where *SSE* is the sum of squared residuals, and *SST* is the total variance of the original signal) was used to calculate the variance explained for the first 4 PCs, separately for the concentric and eccentric phase of each participant. The mean total variance explained was calculated separately for the concentric and eccentric phase of the movement for each participant by varying the number of PCs between one and ten. The minimum number of PCs that accounted for at least 90% of the variance was identified for each participant, separately for the concentric and eccentric phase of the movement.

Statistical analysis:

All statistical analyses were performed using SPSS v.22 (IBM Inc., Armonk, NY, USA). Parametric tests were used if data were normally distributed and had equal variance, non-parametric tests were used if these assumptions were not met. Anthropometric parameters and clinical measures were compared between groups using independent T-tests.

To investigate whether the thickness of subcutaneous tissues differed between females with and without PFP, the thickness was compared between *groups* (PFP or control, between-subject factor), *muscles* (VM or VL, within-subject factor) and *locations* (proximal or distal, within-subject factor) using a 3-way mixed model analysis of variance (ANOVA).

Pooling data across participants for the PCA, and using the PCA to distinguish differences in patterns of activation between groups with and without PFP pain requires the general patterns of activity to be similar within the participants for each group. We tested this by applying PCA to individual participants (separately for females with and without PFP) and then evaluating the Pearson correlation coefficients between the spatial weights for each participant with the mean spatial weights for their group.

The three descriptors of muscle activation identified with PCA were compared. The complexity of muscle activation patterns is reflected by the number of PCs that accounted for at least 90% of the variance, and this was compared between groups using Wilcoxon tests, separately for the concentric and the eccentric phase of the movement. To describe whether the spatial localization of the PCs was similar between groups, Pearson correlation was run on the spatial weights of the first four PCs between groups. PCs with spatial weights that correlated with $R>0.95$ were considered similar between groups. When PCs for the two groups were not significantly correlated, the maps of spatial weights across electrode sites was view qualitatively to identify differences in distribution that would explain the between-group difference. For PCs with a similar spatial structure ($R>0.95$), it was considered valid to compare the temporal coefficient of activation of the vasti muscles between *groups* and *phases* (concentric or

eccentric, within-subject factor) using 2-way mixed model ANOVA, separately for each component. Student's t-tests with Bonferroni correction for multiple comparisons were used for post-hoc comparisons. For PCs with spatial structure that differed between groups, temporal coefficients were compared between the phases (concentric and eccentric) only using paired Student's t-tests.

To identify any relation between clinical measures and EMG dysfunction, Spearman correlation was used to test associations between the EMG indices that were significant in the between-group comparisons and KES, nKES, dynamic midfoot width and dynamic foot height. Statistical significance was set at $p<0.05$.

RESULTS:

Participant characteristics and clinical tests:

The two groups did not differ for age (participants PFP: 27±4; controls: 26±4 years old, $p=0.38$), weight (62±9 vs. 58±9 kg, $p=0.10$), height (166±8 vs. 168±9 cm, $p=0.59$), or physical activity level (4018±2961 vs. 3153±2034 METmin/week, $p=0.20$). A significant difference was identified for body mass index, although the average value for both groups fell within the normal range (22.5±5.2 vs. 20.6±1.7, $p<0.01$). Participants with PFP reported a history of knee pain for 12-60 (interquartile range) months, average pain of 4.1±1.3 in the previous week and their Anterior Knee Pain Score was 74.8. Both KES (116.5±30.6 vs. 135.3±32.9 Nm, $p<0.05$) and nKES (1.88±0.54 vs. 2.31±0.41 Nm/kg, $p<0.01$) were lower in females with PFP compared to controls. Foot height mobility (14.3±1.7 vs. 11.8±2.9 mm, $p<0.01$) but not midfoot width (8.8±4.0 vs. 8.2±1.7 mm, $p=0.44$) was higher in females with PFP compared with controls.

Subcutaneous tissue thickness:

Ultrasound measurement of thickness of subcutaneous tissues did not differ between groups (PFP: 9.2±3.5 mm; controls: 8.6±3.5 mm, p=0.42). Subcutaneous tissues were thicker over VL than VM (9.1±3.4 vs 8.0±3.4 mm; main effect of *muscle*, p<0.01), and proximally than distally (9.4±3.8 vs 7.7±2.8 mm; main effect of *location*, p<0.001). No interactions were observed (p>0.25).

Number of principal components:

A lower number of PCs was needed to explain 90% of the variance for participants with PFP (median: 2; 25^{th}-75^{th} percentiles: 2-3; Fig. 4) than for controls (3; 2-4.5) in the concentric phase of the movement (p<0.05). No differences were observed in the eccentric phase of the movement (p=0.20). These results were confirmed when the variance explained (calculated by applying PCA on each participant separately) was compared between groups (p<0.05). Given that four PCs explained 92.2±4.0% and 94.7±2.4% for controls and participants with PFP respectively (N=20 and N=36; figure S1, variance explained by different number of PCs), all remaining analyses were performed using the first four PCs.

Spatial features of principal components:

The median correlation coefficient between spatial weights extracting using PCA separately for each participant and their group average spatial weight was high (median (interquartile range); PC1: 0.75 (0.67-0.85); PC2: 0.97 (0.94-0.99); PC3: 0.80 (0.72-0.88); PC4: 0.81 (0.47-0.88); all N=56), supporting the use of PCA on group data. Visual assessment of the spatial location of the PCs enables the determination of regional activation patterns described by each PC. PC1 which we refer to as $PC1_{General\ activation}$,

had positive spatial weights for all the channels, describing simultaneous activation of both vasti, and was similar between groups (R = 0.96). The PCs other than $PC1_{General\ activation}$ had both positive and negative values in their spatial weights and temporal coefficients, and described modulation (increase and decrease of activation) of $PC1_{General\ activation}$ (22). In control participants (Fig. 2), PC3 has positive spatial weights (light shading) in the distal region of both VM and VL, and negative values (dark shading) proximally. When the temporal coefficients are positive, muscle activation increases in the channels with positive spatial weights (distally) and decreases where they are negative (proximally); by contrast, when the temporal coefficients are negative, muscle activation increases proximally (channels with negative spatial weights) and decreases distally (channels with negative spatial weights). Taken together, PC3 in controls describes co-activation of the distal region of VM and VL (when the temporal coefficients are positive; start of concentric and end of eccentric) and of the proximal regions (when the temporal coefficients are negative; start of concentric and end of eccentric); for this reason, it was referred to as $PC3_{Vasti\ co\text{-}activation}$. $PC3_{\ Vasti\ co\text{-}activation}$ differed between groups (R = 0.75); for PPF PC3 described regional activation within the VL that was similar to controls, but no concomitant regional activation in VM. In controls PC4 described the co-activation of proximal VL and distal VM or vice versa (Fig. 2), and was referred to as $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$. This was different in PFP (R = 0.73) where $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$ identified regional activation within the VM similar to controls, but did not represent VL activation (Fig. 3). The spatial weight values for PC2, were positive for VM and negative for VL, hence describing a bias to

326 contraction for VM from this PC, thus referred to as, $PC2_{Vastus\text{-}specific\ activation}$. The spatial
327 distribution of $PC2_{Vastus\text{-}specific\ activation}$ was similar between groups (R = 0.99).
328 **Temporal features of principal components:**
329 As the spatial weights of $PC3_{Vasti\ co\text{-}activation}$ and $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$
330 differed between groups in their location, temporal coefficients could not be directly
331 compared for these PCs. Thus, only temporal coefficients of $PC1_{General\ activation}$ and
332 $PC2_{Vastus\text{-}specific\ activation}$ were compared between groups. $PC1_{General\ activation}$ was more
333 active in the concentric than the eccentric phase of the movement (main effect of *phase*,
334 $p<0.001$; Fig. 5) and this did not differ between groups (main effect; $p=0.14$, interactions
335 $p=0.99$). A significant interaction was identified between *groups* and *phases* for the
336 temporal coefficient of $PC2_{Vastus\text{-}specific\ activation}$ ($p<0.05$, Fig. 5), meaning that redistribution
337 of VM/VL activation between the concentric and the eccentric phase of the movement
338 was lower in participants with PFP compared to controls (i.e.: participants with PFP had
339 more co-activation of VM and VL). Both groups showed negative $PC2_{Vastus\text{-}specific\ activation}$
340 temporal coefficients (i.e. activation to expression of PC2, and thus bias to VL
341 activation) in the concentric phase of the movement and positive $PC2_{Vastus\text{-}specific\ activation}$
342 temporal coefficients (bias to VM activation) in the eccentric phase of the movement;
343 this resulted in significantly lower temporal coefficients during the concentric phase than
344 the eccentric phase of the movement ($p<0.001$). In controls, the temporal coefficients of
345 $PC3_{Vasti\ co\text{-}activation}$ (0.02±0.26 and 0.03±0.23, $p=0.67$) or $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$
346 (0.01±0.20 and 0.02±0.17, $p=0.36$) did not differ between concentric and eccentric
347 phase of the movement. In PFP, $PC3_{Within\text{-}VL\ activation}$ was lower in the concentric than the
348 eccentric phase of the movement (-0.02±0.26 and 0.03±0.17, $p<0.05$); a similar

tendency, although not-significant, was observed for $PC4_{Within\text{-}VM\ activation}$ (0.00±0.15 and 0.03±0.17, p=0.06).

Associations between clinical tests and neuromuscular activation patterns:

Correlations were assessed separately for participants with and without PFP to investigate associations between the EMG indices that were found to differ significantly between groups (temporal coefficients of $PC2_{Vastus\text{-}specific\ activation}$; number of PCs necessary to reconstruct 90% of the variance in the concentric phase of the movement; see above) and clinical measures (KES; nKES; midfoot width; foot height). One individual was identified as a potential outlier and this was statistically confirmed by inputting the data to a linear regression model. For that participant, Cook's distance measures were 0.93 (temporal coefficients of $PC2_{Vastus\text{-}specific\ activation}$ and nKES) and 0.95 (temporal coefficients of $PC2_{Vastus\text{-}specific\ activation}$ and KES), much higher than the cut-off value for outliers (4/N=0.11). After exclusion of data for that individual, an inverse correlation was identified between temporal coefficients of $PC2_{Vastus\text{-}specific\ activation}$ during the eccentric phase of the movement and KES (p=0.01, R=-0.43; nKES: p=0.001, R=-0.52; Fig. 6), that is, participants with a lower redistribution of activation between VL and VM had higher KES. Association in the same direction was observed for temporal coefficients of $PC2_{Vastus\text{-}specific\ activation}$ during the concentric phase of the movement, although the strength of the association was lower (KES: p<0.05, R=-0.38; nKES: p=0.09, R=-0.3). These associations were not observed in females without PFP (p>0.12, R<0.36). No other significant correlations were identified.

DISCUSSION:

These data show that the regional activation within VM and VL during a low-force dynamic knee extension task differs between females with and without PFP. The lower number of PCs needed to reconstruct 90% of the variance (i.e. fewer components required to explain the pattern of EMG activity) for those with PFP than controls, and the lesser difference in bias to VM or VL between the concentric and eccentric task phases, both suggest a simpler control strategy of vasti muscle coordination in PFP. The data also show lower co-activation between VM and VL in PFP than in controls; PC3 and PC4 represented activation of only VM or VL in the PFP group, unlike the controls where these PCs represented coordination between the vasti muscles. The inverse association between task specificity of VM/VL coordination and maximal knee extension strength in PFP demonstrates a spectrum of presentations with lower knee extension strength but VM/VL coordination that was similar to controls at one end, and high knee strength but compromised VM/VL coordination at the other end.

Altered VM and VL activation patterns have been observed in PFP in this study. During the concentric phase of the knee extension, vasti muscle activation of females with PFP can be explained by two main activation patterns, i.e.: global activation (PC1) and redistribution between VM and VL (PC2). To reconstruct the signal to a similar extent (i.e. explain the same amount of variation), the control participants required inclusion of an additional activation pattern that represented co-activation of distal or proximal regions of VM and VL. This observation suggests that activation of the VM and VL in PFP participants included a smaller component of EMG that controlled coordination between medial and lateral forces during muscle shortening. Similar findings of simpler control in association with a musculoskeletal condition has been

reported for the deep hip external rotator muscles in participants with femoro-acetabular impingement syndrome (28). During the eccentric phase, the number of PCs did not differ between groups; however, the additional activation patterns in PFP represented regional activation of a single vastus muscle, rather than coordination between of regions between VM and VL. This concurs with observation of less synchronous activation of motor units in VM and VL in PFP (3) and other studies that identified differences in timing and amplitude of vasti activation using conventional bipolar surface EMG (4, 30).

Taken together, the present results suggest that a PC that accounts for co-activation between regions of VM and VL explains an important component of pattern variance in controls but not in PFP. Consistent with proposed theories of patellofemoral joint control (1, 31), this co-activation between VM and VL could be interpreted to represent a strategy coordinate forces for optimal patellar tracking in controls. Females with PFP used patterns of EMG that involved lesser modulation of regional activation within each vastus, but instead used overall co-activation plus components that account for bias of activity to only VM or VL. It has been shown *in vivo* that load applied by each vastus muscle in isolation influences the distribution of forces applied to the patella (21, 32). It is plausible that this would be impacted by the distribution of activity between the vasti muscles and differences in this pattern between controls and participants with PFP could be expected to alter patellar kinematics and pressure distribution within the patellofemoral joint observed in PFP (30, 33).

An interesting observation was the between-group differences in the task specificity of the relative activation of VM and VL during phases of dynamic knee

418 extension. As control participants showed a bias towards VL activation during the
419 concentric phase and towards VM activation during the eccentric phase of the knee
420 extension movement, this may have significance for differences in patellar tracking and
421 joint loading between the different tasks. This between-muscle redistribution of EMG
422 was limited in PFP, especially during the eccentric phase of the movement. Reduced
423 task specificity has also been observed in some other musculoskeletal conditions, such
424 as low back pain (34) and may imply a loss of the fine-tuning of the control of forces in
425 the patellofemoral joint. Te and colleagues (35) have recently shown that the
426 representations of the individual heads of the quadriceps on the motor cortex are closer
427 together for individuals with PFP than healthy controls; similar to what was suggested in
428 other studies (36, 37). Although speculative, such merging of the muscle
429 representations at the cortical level may underlie a lesser capacity to modulate
430 coordination of vasti muscles in a task specific manner. However, we cannot interpret
431 from our data where in the nervous system changes might be occurring (e.g. cortical,
432 spinal, etc) and further work is required.

433 The temporal coefficients of $PC1_{General\ activation}$ suggest a greater contribution of
434 this PC during the concentric than eccentric phase of the movement, without a
435 difference between groups. This suggests that the lower muscle activation in the
436 eccentric versus the concentric phase of movement (38) is preserved in PFP and would
437 be expected base on physiological property of muscle to require less EMG activation to
438 generate equivalent force in eccentric contractions. The co-activation patterns ($PC3_{Vasti}$
439 $_{co\text{-}activation}$ and $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$) in controls were equally observed in the
440 concentric and eccentric phase of the movement, suggesting that the within-muscle

441 redistribution of activation represented by these PCs occurred similarly for both tasks.
442 Unlike the control participants, the within-muscle regional activation patterns ($PC3_{Within-VL\ activation}$ and $PC4_{Within-VM\ activation}$) in PFP indicated preferential activation of one muscle
444 rather than co-activation, specifically the distal VL ($PC3_{Within-VL\ activation}$) and VM ($PC4_{Within-VM\ activation}$, trend) in the eccentric phase of the movement, similar to previous
446 preliminary observations in the VM (16). This suggests that preferential activation of
447 vasti regions that have larger potential to contribute to medio-lateral patellar forces
448 mainly occurs in the eccentric phase of the movement. Although this aspect of the
449 motor pattern was more task specific for PFP and controls, and is not consistent with
450 our suggestion of a simplified control strategy in this group, it must be taken together
451 with the fact that these PCs only explain a small percentage of the variance.
452 Regardless, this observation remains interesting because, in contrast to control
453 participants, this within-muscle redistribution was not co-activation and occurred at
454 different times for two muscles. These findings highlight differences in how females with
455 and without PFP activate the distal regions of VM and VL in dynamic contractions.

456 Contrary to our hypothesis, participants with lower knee extension strength did
457 not show the largest differences in neuromuscular control (lower redistribution between
458 VM and VL). Instead, an inverse association was observed – the weaker participants
459 had a neuromuscular activation pattern more like controls. A recent classification
460 identified two categories of adaptation to pain: major “movement avoidance” patterns
461 and subtle “redistribution within and between muscle” (39). The current data provide an
462 interesting new observation – we propose an interpretation that the adaptations in
463 females with PFP are distributed along a continuum, with some presenting with a

464 “reduced force output” strategy, whereas others present with subtle differences in
465 muscle coordination. There is of course a proportion of the PFP group with strength and
466 neuromuscular activation between these two extremes. The lower force output may be
467 associated not only with neuromuscular factors, but also to changes in muscle structural
468 parameters (40). Regardless, these two different strategies may present with different
469 consequences for long-term health of the patellofemoral joint.

470 Because of the cross-sectional design of the study, it is not possible to define
471 whether changes in force output and neuromuscular activation are a cause or
472 consequence of PFP, or whether in the long term the effects on patellofemoral joint
473 health are different. Regardless, it is tempting to speculate about the potential clinical
474 implications as it may be helpful to identify subgroups of participants that respond
475 differently to interventions. Specifically, females with PFP and lower knee extension
476 strength may benefit from interventions that focus on quadriceps strengthening,
477 whereas exercises that target motor control might be beneficial for females with PFP
478 and knee extension strength similar to controls, but concomitant differences in
479 coordination of vasti muscles. Future studies should investigate whether interventions
480 matched to these deficits in females with PFP have better clinical outcomes than
481 treatments that are not matched.

482 Due to conduction volume of soft tissues, surface electromyographic signals are
483 known to be influenced by crosstalk. One of the main contributors to crosstalk in the
484 surface EMG is the thickness of subcutaneous tissues. Despite larger BMI in females
485 with PFP, ultrasound measures of subcutaneous tissue thickness over VM and VL did
486 not differ between groups (average difference: 0.6 mm). For this reason, any effects of

subcutaneous tissue thickness on the crosstalk in the surface EMG activation patterns would be similar between groups. Additionally, crosstalk from far sources is likely to be observed as similar EMG amplitude fluctuations in most channels of the grid, represented by PC1 in this study, while the other PCs representing regional activation may be less influenced by crosstalk. While the amount of crosstalk present in this dataset cannot be precisely defined, the absence of differences between group in thickness of subcutaneous tissue and the use of PCA suggest that crosstalk had a minimal influence on the results of this study.

In conclusion, females with PFP have simpler VM and VL activation strategies, observed as lower co-activation of regions between VM and VL and lower redistribution of activation from VL to VM when the concentric and eccentric phases of the knee extension are compared. As VM/VL redistribution was inversely correlated to maximal knee extension strength, we suggest two different presentations of PFP: prevalent lower knee extension strength or prevalent lower redistribution between VM and VL. These dysfunctions may be preferentially targeted by different interventions, potentially resulting in improved clinical outcomes.

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The authors declare no conflicts of interest.

Results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Results of the present study do not constitute endorsement by the American College of Sports Medicine.

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604 kinematics following a femoral nerve branch block of the vastus medialis:
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629 Supplemental Figure 1.tif

FIGURES:

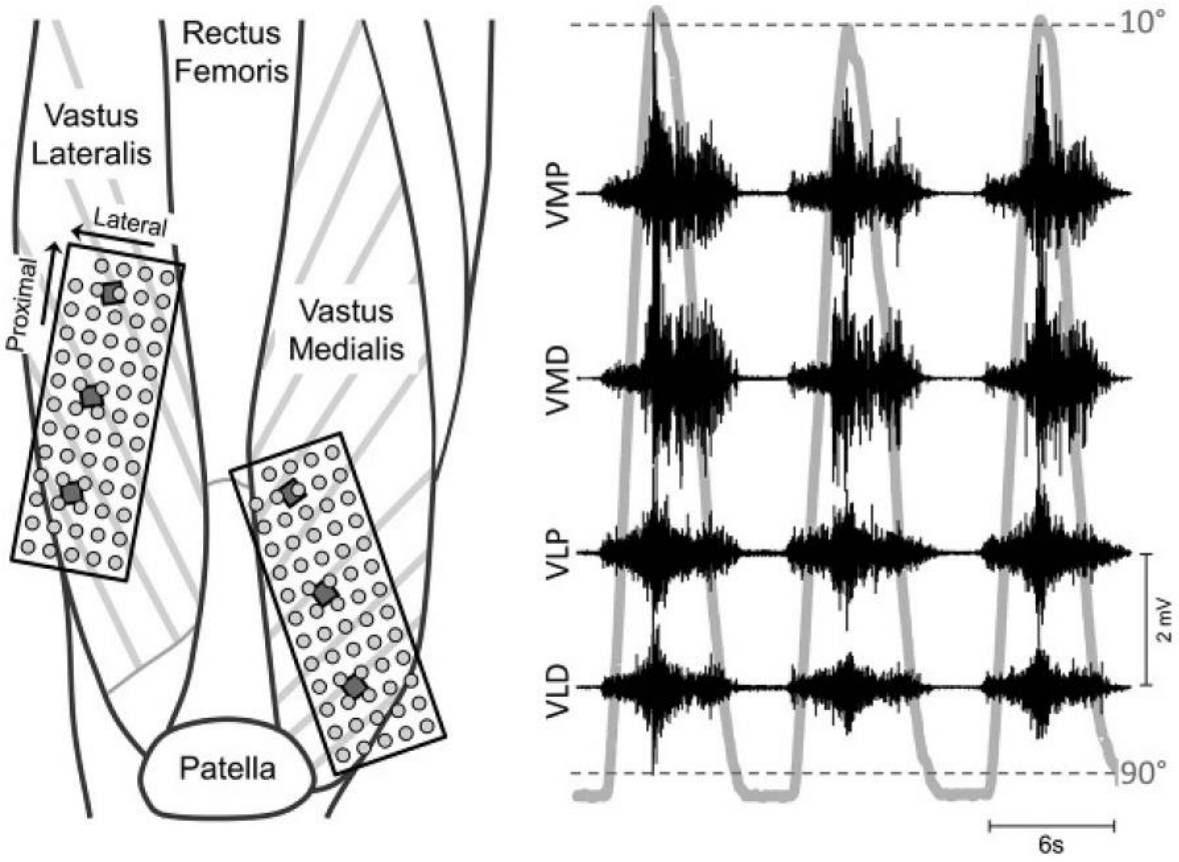


Figure 1: Experimental set-up. Left: placement of the electrode grids on vastus medialis (VM) and vastus lateralis (VL). Gray squares identify the innervation zones. Right: example of knee joint angle (thick gray line) and monopolar surface EMG collected from proximal (P) and distal (D) locations within VM and VL.

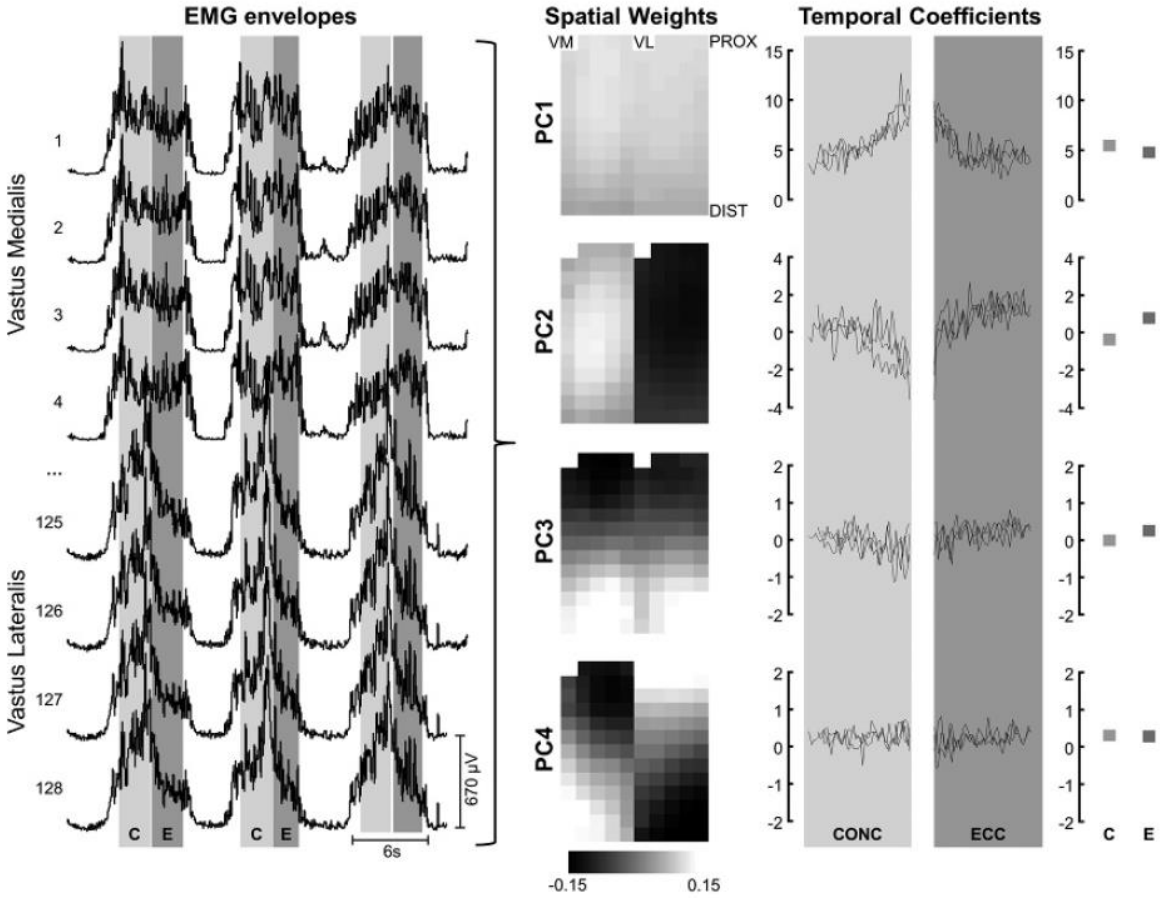


Figure 2: Example of PCA analysis of high-density EMG signals for a control participant. Left: 8 of the 128 EMG envelopes used for the PCA from 3 repetitions of a control participant; light and dark gray boxes identify the concentric (C) and eccentric (E) phase of the movement (10-90°). Middle: spatial weights of PC1-4 (from PCA using data for all control participants); light and dark shades identify positive and negative weights respectively. $PC1_{General\ activation}$ shows positive weights for both VM and VL; $PC2_{Vastus\text{-}specific\ activation}$ shows positive weights of VM and negative weights for V**L**; $PC3_{Vasti\ co\text{-}activation}$ shows positive weights for both muscles distally and negative weights proximally; $PC4_{Proximal\text{-}distal\ vasti\ co\text{-}activation}$ shows positive weight for VM distally and VL proximally, and negative weights for VM proximally and VL distally. Right: temporal coefficients

calculated from the same three repetitions on the left, and average temporal coefficients calculated over 10 repetitions, separately for concentric and eccentric phase. Inspection of coefficients suggests that expression of $PC1_{General\ activation}$ increases towards the end of concentric motion and beginning of eccentric motion. The converse is shown for $PC2_{Vastus\text{-}specific\ activation}$ (and $PC3_{Vasti\ co\text{-}activation}$ to a lesser extent); lower towards end of concentric and beginning of eccentric. Some differences were observed between phases and groups, when analyses are appropriate (i.e. $PC1_{General\ activation}$ and $PC2_{Vastus\text{-}specific\ activation}$ which both had no difference in spatial coefficients between groups).

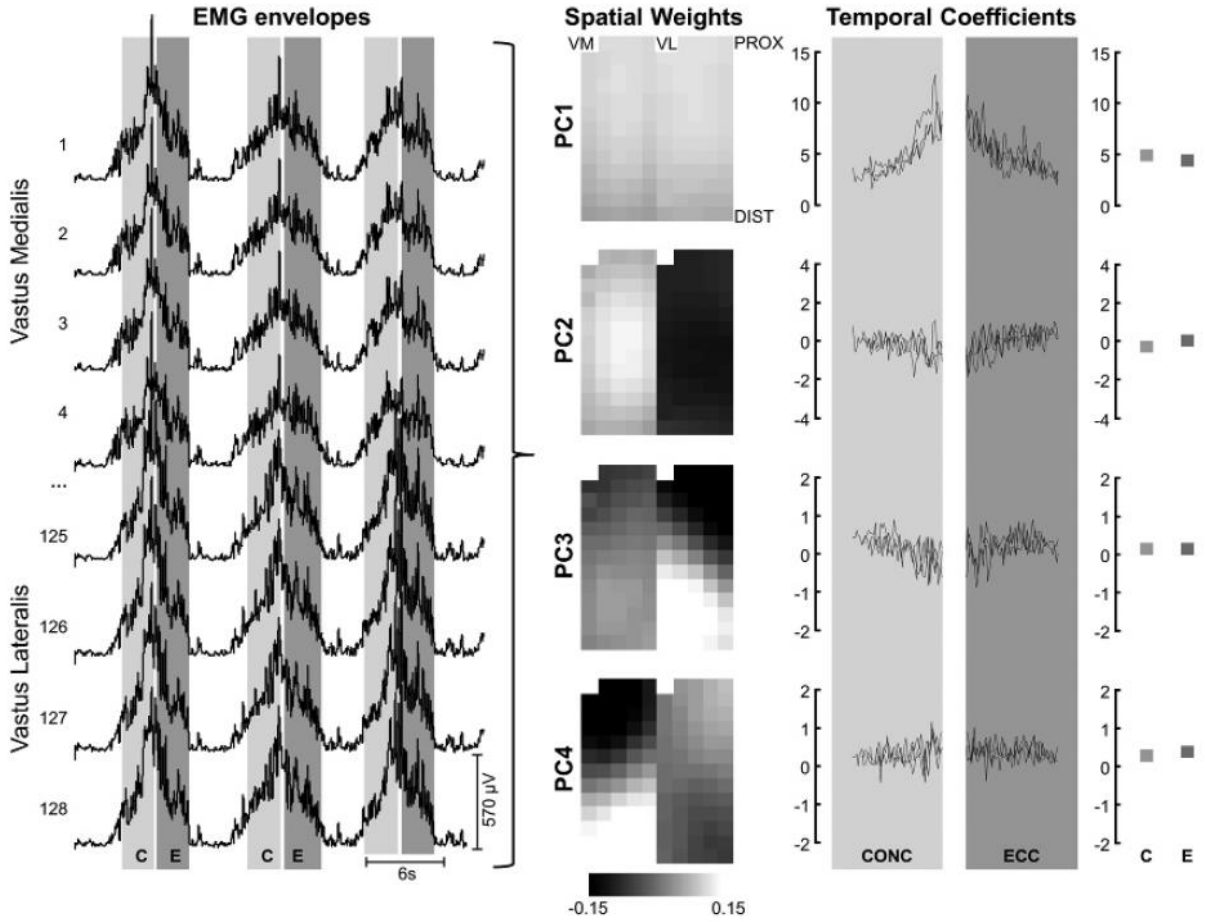
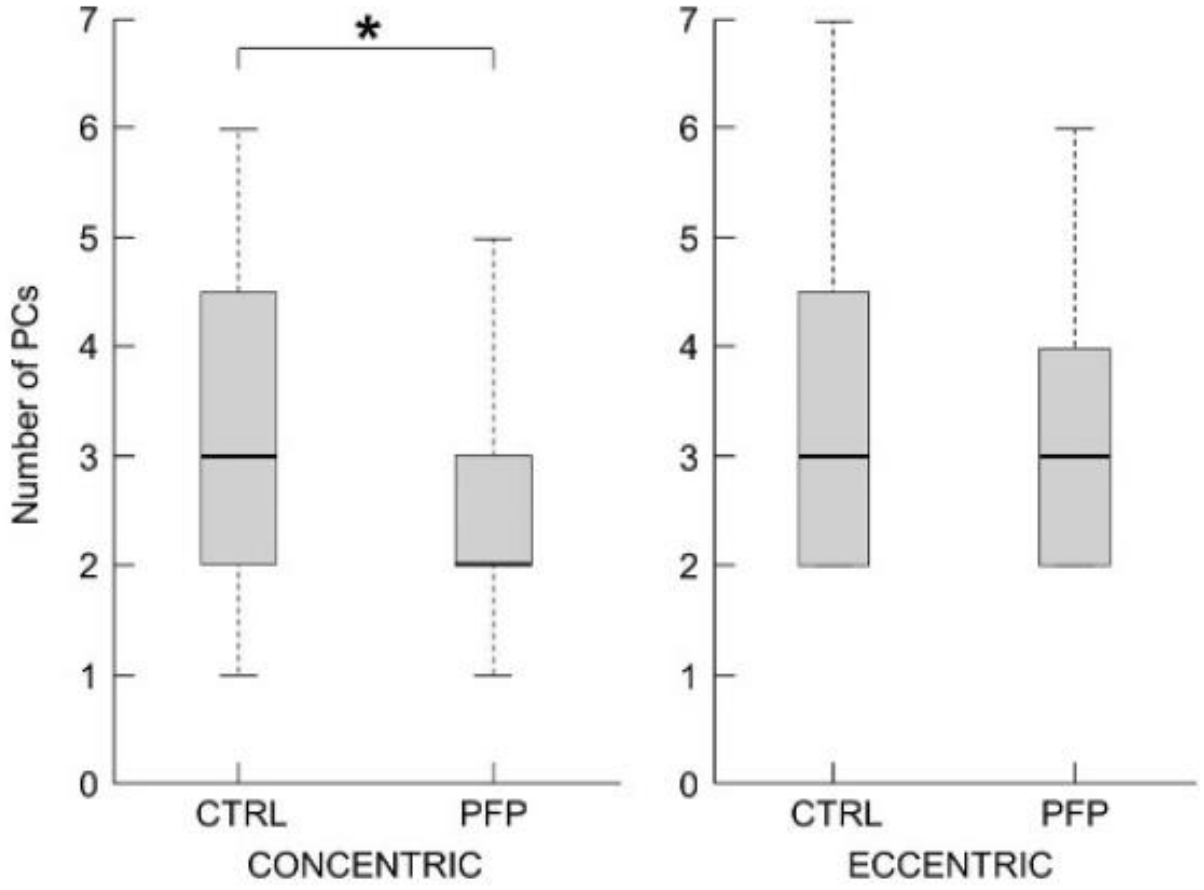


Figure 3: Example of PCA analysis of high-density EMG signals for a participant with PFP. Left: 8 of the 128 EMG envelopes used for the PCA from 3 repetitions of a control

658 participant; light and dark gray boxes identify the concentric (C) and eccentric (E) phase
659 of the movement (10-90°). Middle: spatial weights of PC1-4 (from PCA using data for all
660 the participants with PFP); light and dark shades identify positive and negative weights
661 respectively. Weights for PCs are similar to that for control participants (see Fig. 2),
662 except, unlike controls, $PC3_{Within\text{-}VL\ activation}$ and $PC4_{Within\text{-}VM\ activation}$ reflect activity of single
663 muscles rather than a pattern of coordination between muscles (no regional variation in
664 VM in $PC3_{Within\text{-}VL\ activation}$ or VL in $PC4_{Within\text{-}VM\ activation}$). Right: temporal coefficients
665 calculated from the 3 repetitions on the left, and average temporal coefficients
666 calculated over 10 repetitions, separately for concentric and eccentric phase. Only
667 temporal coefficients for $PC1_{General\ activation}$ and $PC2_{Vastus\text{-}specific\ activation}$ were compared
668 between groups for both control and PFP groups.



669

670 Figure 4: Comparison between the minimum number of PCs that explains at least 90%
671 of the variance in the concentric (left) or eccentric (right) phase of the movement. *
672 $p<0.05$

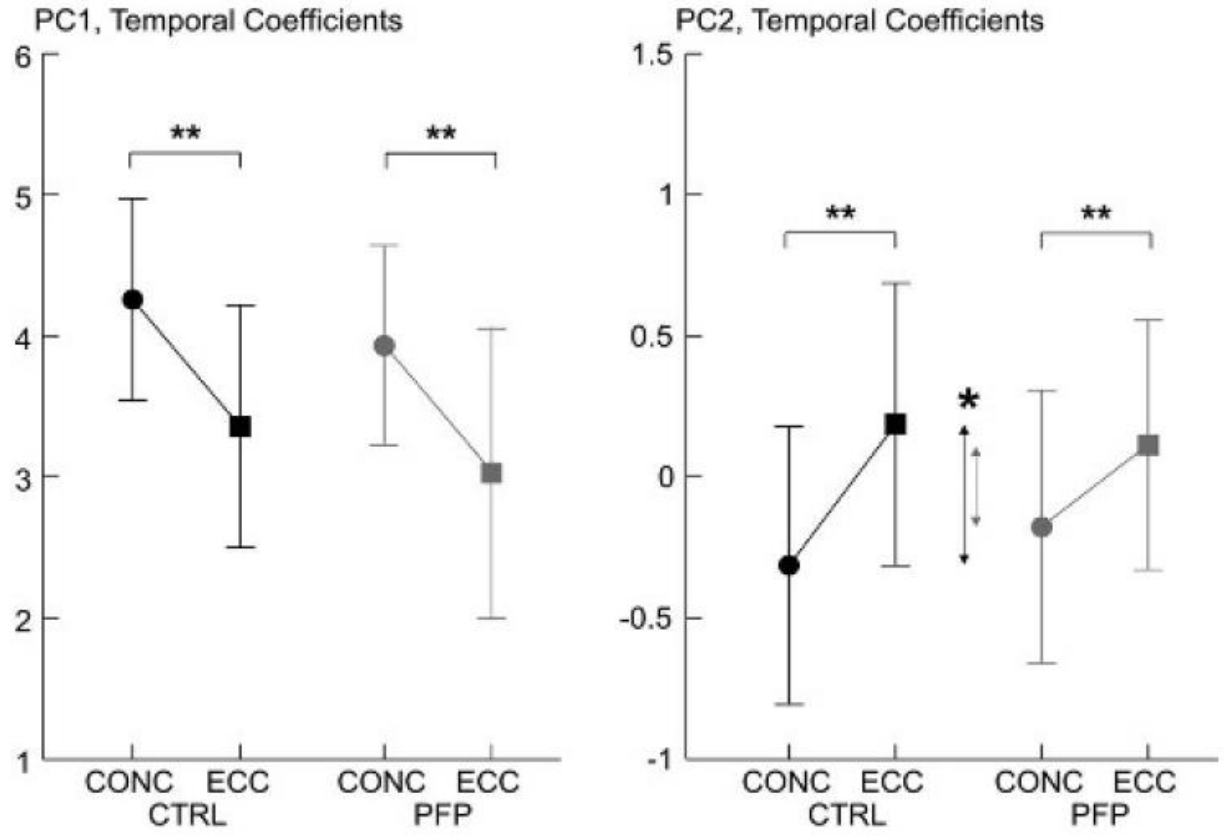
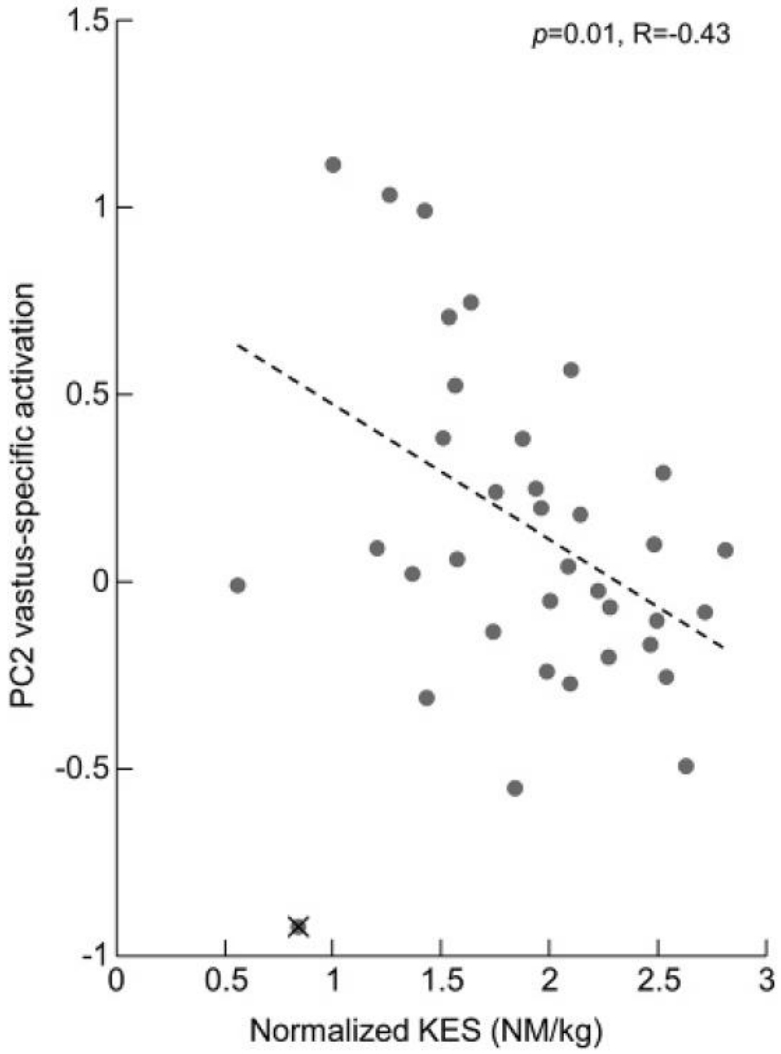


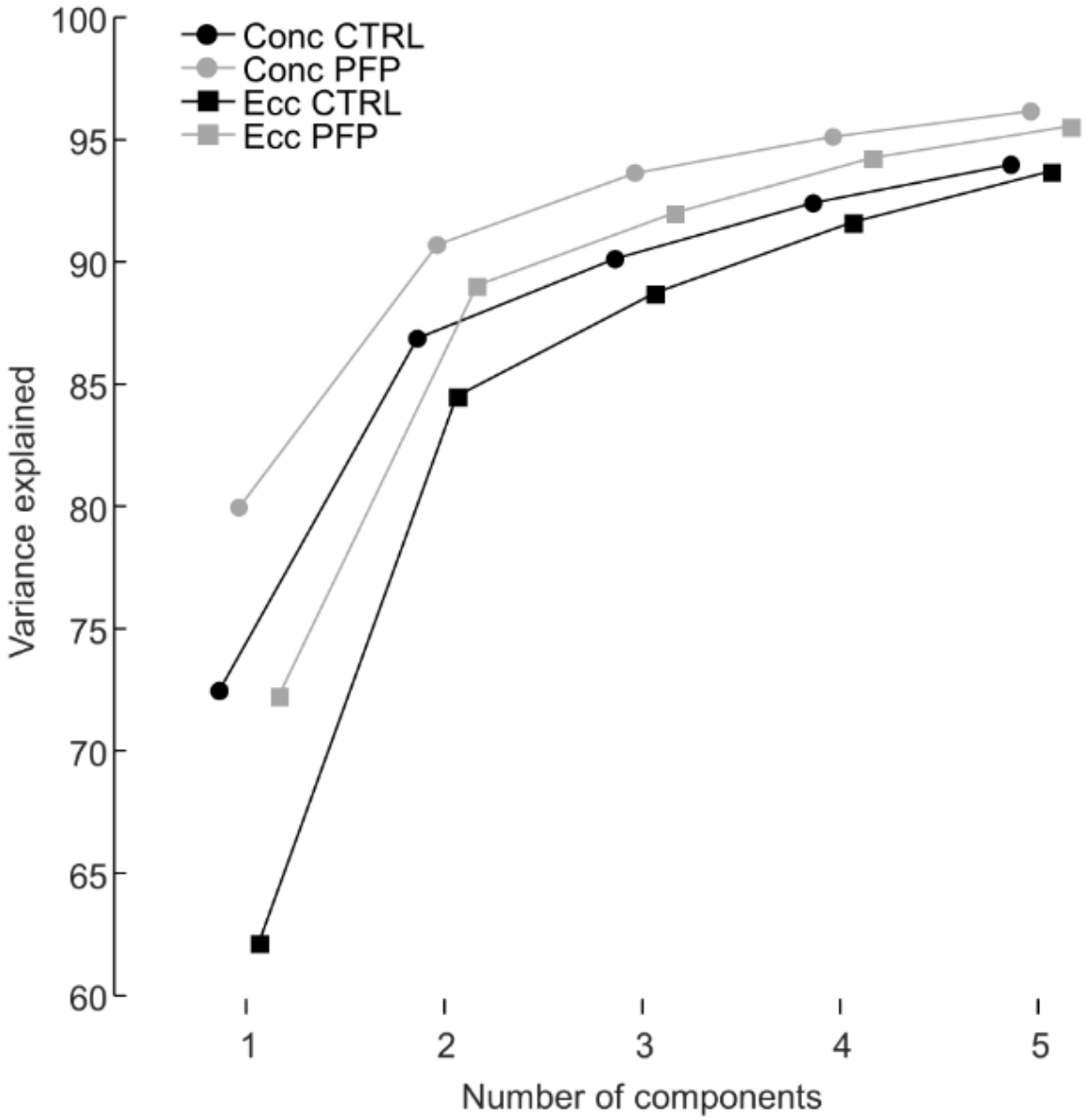
Figure 5: Figure 5: Comparison of mean temporal coefficients of $PC1_{General\ activation}$ (left) and $PC2_{Vastus\text{-}specific\ activation}$ (right). The contribution of $PC1_{General\ activation}$ was larger during the concentric than the eccentric phase of the movement, regardless of the group. For both groups, $PC2_{Vastus\text{-}specific\ activation}$ was negative (prevalent VL activation) in the concentric and positive (prevalent VM activation) in the eccentric phase of the movement; however, this redistribution was smaller in the PFP than in control participants (interaction effect identified by the arrows). * p <0.05; ** p <0.01



681

682 Figure 6: Scatter plot of KES and $PC2_{Vastus\text{-}specific\ activation}$ (eccentric phase) in females with
683 PFP; higher values indicate preferential VM activation during the eccentric phase of the
684 contraction. The data point of the participant excluded from this analysis was crossed.
685 Spearman R identified a moderate inverse correlation between the two variables.

686



687
688 Figure S1: Variance explained by different number of PCs. Gray and black lines identify
689 participants with and without PFP. Circles and squares identify concentric and eccentric
690 phases of the movement.